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PRACTICAL TOOLS

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A bespoke low-cost system for radio tracking animals using multi-rotor and fixed-wing unmanned aerial vehicles

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Abstract

1. Due to the costs of related technologies, tracking studies typically use low numbers of animals as representative samples for whole group or species analysis, often without clear knowledge as to how representative these numbers are.
2. The use of unmanned aerial vehicles (UAVs) has the potential to considerably improve radio-frequency (RF)-based tracking systems. This includes improved line-of-sight visibility, access and range in difficult terrain and an increase in achievable spatial accuracy.
3. This paper presents details of a fully custom-built active RF identification tag and receiver system bespoke to UAVs, compatible with both multi-rotor and fixed-wing platforms. Using sheep as a model, we show the suitability of this system for tracking large terrestrial mammals.
4. During static testing using both platform types, we calculated a spatial accuracy of 58.5 m (based on 95th percentile/R95 parameter) for this system using data from 14 flights (n = 175 tag interactions). When tested on sheep, working tags were detected 93% of the time over seven conducted flights.
5. We provide practical considerations for operating this system on a UAV platform, address concerns relating to the system and identify future areas of research both for this system and other UAV-based RF tracking systems.

KEYWORDS
agricultural systems, applied ecology, conservation, monitoring

1 | INTRODUCTION

The spatial and temporal distribution of animals is frequently a foundation for understanding biological phenomena within physiological, behavioural and ecological studies (Kays, Crofoot, Jetz, & Wikelski, 2015). The increased utilization of GPS in recent years has led to refinement in the achievable accuracy of animal tracking devices, and reductions in the labour required to operate them. However, with this has come an increase in cost which often corresponds to low numbers of animals being tracked, and the assumption that the positional information of a subset of individuals is representative of whole herd/group movements. Whilst radio-frequency (RF) tags cannot provide the continuous tracking capability of GPS-equipped trackers, they are inexpensive and can be extremely small and lightweight, allowing large number of animals to be tracked albeit at lower spatial precision and frequency.

Advances in the autonomous capability and payload capacity of unmanned aerial systems have led to them being increasingly utilized and explored as potential data collection platforms in ecological surveying and monitoring (Hodgson et al., 2018). The ability of unmanned aerial vehicles (UAVs) to travel long ranges quickly (particularly fixed-wing UAVs) whilst offering greater predictable likelihood of line-of-sight of target animals (Körner, Speck, Göktogan, & Sukkarieh, 2010) provides advantages over conventional methods of radio tracking on the ground.

Recently, researchers have begun to explore the potential benefits of UAV-based radio tracking systems (hereon referred to as UAVRTS) compared to conventional methods. However, as Shafer, Vega, Rothfus, and Flikkema (2019) note, many of the presented systems exist primarily as proof-of-principle concepts. The prime focus in most of these studies is the refinement of the localization methods employed. Whilst this may be valuable in considering potential hardware configuration options, there remains sizeable knowledge gaps within the subject area that have delayed the development of field-ready systems. Firstly, there has been very limited testing on animals, with tagging to date almost exclusively restricted to avian species (Cliff, Fitch, Sukkarieh, Saunders, & Heinsohn, 2015; Tremblay, Desrochers, Aubry, Pace, & Bird, 2017). Furthermore, many studies are limited to single tag testing (Bayram, Stefas, & Isler, 2018; Dos Santos et al., 2014; Körner et al., 2010; Shafer et al., 2019), and thus, their ability to track movements when multiple animals are tagged remains unknown. Furthermore, none of the studies have utilized or tested their systems on fixed-wing UAVs. Given that fixed-wing UAVs offer vastly superior range, flight speed and endurance compared to multi-rotor platforms, there is an opportunity to greatly expand the capability of UAVRTS by using such a platform.

The novel system reported in this paper features a fully custom-made active RF identification (RFID) tag and receiver system suitable for both fixed-wing and multi-rotor UAVs. The electronic components are purposely low cost with the goal of making tagging greater numbers of animals more affordable. Unlike previous studies where existing commercial tags have been used or modified, we present a bespoke tag specifically designed for detection by a UAVRTS. Whereas most existing tags continually transmit when activated, our RFID tags remain in a dormant state, with a brief listening period occurring every 6 s. Tag responses are only elicited when a tag exciter trigger located on the UAV comes into operation, thereby saving considerable battery life. The receiver system is also contained within a single printed circuit board (as opposed to the multi-component set-ups utilized within previous studies) which substantially reduces the overall weight and the likely mean time between failure (MTBF).

Previous UAVRTS have focused on incorporating and modifying either direction (e.g. direction of arrival) or range-based techniques (e.g. received signal strength) as methods of locating tags. We explored an alternative localization method. Using grid flight mission functionality available in both open-source and commercial autopilot systems, we derived estimated tag locations by a simple mean coordinates calculation (Figure 1). The assumption of equal coverage of the surveyed area (provided by the flight grid) and the notion that the grid exceeds the range of the tag (i.e. so-estimated locations are not simply the centre of the grid) are central to accurate tag location by this method. By flexibly altering the transmission power of the tag trigger exciter depending on the size of the grid employed, we ensure signal loss at grid edge regardless of the situation.

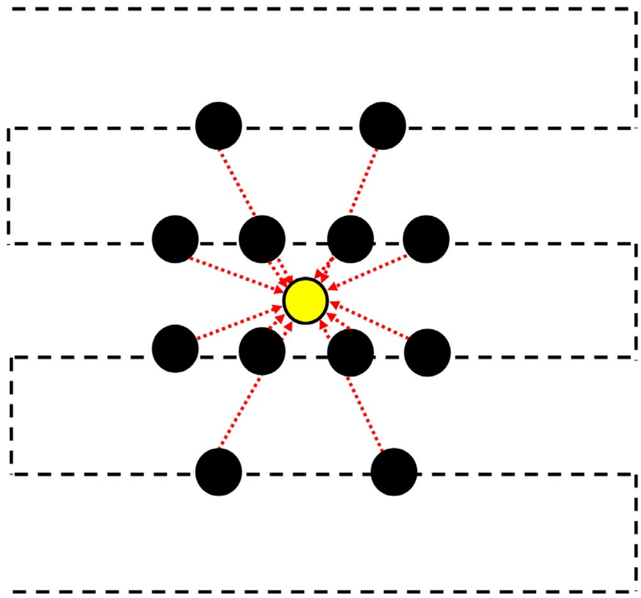

FIGURE 1 Locating tags using mean coordinates. Black line = unmanned aerial vehicle (UAV) flight grid. Black dots = receiver location when tag transmission was detected. Yellow dot = estimated tag location based on mean coordinates of black dots

To our knowledge, this method of localization is undocumented for UAVRTS. We therefore sought to explore the level of accuracy deliverable, and the operational considerations that could affect it. We considered flight speed to be the key interest, exploring (a) the effect it had on the number of hits (tag responses) received and (b) how this affected the accuracy of a determined tag location. Beyond this, we then sought to test the real-world applicability of this system. Further objectives therefore included (c) assessing the cross-compatibility of our UAVRTS to function on both multi-rotor and fixed-wing UAVs and (d) measuring the performance and reliability of the system with tags placed on animals.

2 | METHODS

2.1 | RFID tag system design

The main components in each RFID tag (Figure 2) were a PIC10F206 microcontroller (Microchip Technology Inc) and a HopeRF RFM69W radio transceiver (Hope Microelectronics co., Ltd) operating in the 868 MHz band. These were mounted on a custom-printed circuit board with integrated antenna and were powered by a single-cell 60 mAh lithium polymer (LiPo) cell. The microcontroller was programmed to wake the radio module approximately once every 6 s for approximately 2 ms. During this 2-ms period, the radio module detected the signal from the trigger module (if one was present), switched to a different radio channel and responded using a simple medium access control delay mechanism with a radio packet containing a unique identifier for the tag. The response was transmitted three times, again using a simple medium access control delay mechanism to help reduce collisions between packets from different tags. In the absence of a signal, the microcontroller returned all components to a low power sleep state until the next listening window 6 s later. Predicted battery life in the absence of a trigger signal is over 1 year, but each transmission triggered will reduce the battery life by around 1 hr. Responses from the tags were recorded by the UAV-mounted receiver module which used a HopeRF RFM69W radio transceiver, a Quectel L86 GPS receiver (Quectel) and an ATMega328P microcontroller (Microchip Technology Inc). The microcontroller decoded the packets received from the RFID tag and saved the tag unique identifier, latitude and longitude of the receiver and timestamp to a removable microSD memory card. With a clear line-of-sight and using a 10-mW transmitter power in both directions (from trigger to tags and tags to receiver), the range achievable varied between 500 and 800 m. Total weight for the system on the UAV was 195 g; this included receiver box (115 g), trigger (80 g), batteries and cable ties. Each RFID tag weighed 9 g. At the time of writing, the estimated cost was £160 (£135 for receiver, £25 for trigger) with each RFID tag priced at just under £12.

FIGURE 2 Custom-built radio-frequency identification tag

2.2 | UAV set-up and RFID tag system integration

Multi-rotor: The platform was a DJI Phantom 3 professional (DJI). The receiver and tag trigger were mounted onto opposing ends of a 1-m long plastic rod, which in turn was cabled tied to the two landing stands on the drone (Figure 3). The UAV was operated autonomously using the PIX4D capture app (PIX4D) on an Iphone 5S (Apple Inc.).

Fixed-wing: The UAV set-up was similar to that of Ryan et al. (2015). The UAV airframe was a Skywalker X8 (Skywalker). Autonomous flight capability was used (http://ardupilot.com/); this provided flight stabilization, altitude control (including terrain following) and GPS navigation. The tag trigger and receiver were located on opposite wing tips, with each accompanied by a single rechargeable 300 mAh LiPo cell as a power source, which could provide ~2 hr of use (Figure 3). The receiver was encased in a small plastic container wrapped with aluminium foil, except for directly above the GPS module, as initial testing revealed considerable radio interference from the fixed-wing UAV avionics. Additional shielding was also fitted over the speed controller and electrical cables to the motor. The receiver case was bolted onto the wing tip, whilst the tag trigger was attached using cables ties, and the join further strengthened using cross-weave tape.

FIGURE 3 DJI Phantom 3 Pro with radio-frequency (RF) system mounted along a plastic rod attached to under carriage (top left). Skywalker X8 with RF system attached on wing tips (top right). Tag trigger mounted on X8 wing tip (bottom left). RF receiver mounted inside foil wrapped box on X8 wing tip (bottom right)

2.3 | Static accuracy and the effect of UAV flight speed

Multi-rotor: Eighteen RFID tags were split into three groups which were each places at three different locations ~200 m apart ($n = 6$ per group), with every tag within each group equally spaced within a 1-m^2 area. Two GPS loggers (Ystumtec Ltd) were present in each group to provide a reference location. The flight grid consisted of a four-line grid encompassing a 650 × 230 m area. Twelve flights were conducted in total at three different flight speeds based on percentage speed potentials of the DJI Phantom 3 pro, according to the PIX4D capture app, at 70% (~5.3 m/s), 80% (~8.5 m/s) and 100% (~14.5 m/s) of the maximum capable speed. Flight altitude was set to 100 m for all flights.

Fixed-wing: Fixed-wing UAVs are limited by their stall speed. In addition, wind speed affects performance, and thus, it was impractical to attempt to test at varying speeds. Therefore, the accuracy of the tags was only assessed at a single target groundspeed set to 18 m/s. Twelve tags were placed (seven scattered; five within a 1-m^2 area) in a 3.69-ha field, and GPS location referenced (MyGPSCoordinates app; Kevin Willet, TappiApps) (reported accuracy ± 5 m). A flight grid was created ~960 × 960 m (92 ha) in size, which included 19 lines at a spacing of 50 m, and flight altitude set to 100 m.

2.4 | Attaching RFID tags to the sheep

Thirteen Herdwick sheep *Ovis aries* were selected for tag application. Ethical approval was obtained. The work described was conducted in accordance with the requirements of the UK Animals (Scientific Procedures) Act 1986, and with the approval of the Institute of Biological Environmental and Rural Sciences (IBERS) Animal Welfare and Ethical Review Board. Of the 13 sheep, two had a single tag attached to each of their horns, nine had a tag attached to one of their ears and two had tags attached to collars fitted around their necks. In attaching tags to the horns, tags were first dipped in IMPACT adhesive glue (Bostik Ltd), placed on top of the horn facing skywards, wrapped with a crepe bandage, then secured with a layer of RHINO cross-weave fabric tape on top (Ultratape House). Each ear tag was secured to the outside edge of an existing 'loop' management tag using two cable ties. When attached to collars, tags were cable tied to the back of the collar facing upwards. The sheep were held in the same 3.69 ha field where the fixed UAV accuracy testing was undertaken. A similar flight grid was created (~960 × 960 m) and flight altitude set to 100 m. A total of seven missions were completed over a 2-week period.

2.5 | Data analysis

Duplicate hits (as a result of the tag sending three responses per transmission) that shared the same position were deleted. Any duplicate responses that occurred after GPS update were treated as standalone responses as they had differing locations to the first response in the package. Only hits received along the grid lines were used, removing any that were recorded during launch/landing. Mean coordinates (Lat/Long) of each individual tag were subsequently calculated in open-source GIS software (QGIS vers 2.12.3 *Lyon*). For assessing static accuracy, distance (in m) between each calculated tag mean coordinate (Lat2, Long2) and known GPS location (Lat1, Long1) was completed in Microsoft Excel using the following formula, which is based on the Spherical Law of Cosines:

$$\mathrm{acos}(\sin(\mathrm{lat1}) * \sin(\mathrm{lat2}) + \cos(\mathrm{lat1}) * \cos(\mathrm{lat2}) * \cos(\mathrm{long2} - \mathrm{long1})) * 6,371.$$

Statistical analyses were performed using R Studio version 3.6.1 (R Core Team, 2013). The packages MASS (Ripley et al., 2013) and LME4 (Bates, Sarkar, & Matrix, 2007) were required. The 95th percentile of the data was used as a measure of overall static accuracy.

Three regression analyses were performed. Firstly, in order to assess the relationship between accuracy (a positive, skewed, continuous variable), speed (continuous variable with values roughly close to 5, 8, 14 and 18 m/s) and number of hits, gamma regression was used with speed and number of hits as explanatory variables. The functional form (i.e. whether higher order terms for hits were required) was motivated by local polynomial regression. Secondly, a (gamma) mixed effects model was used to provide an estimate of between-tag variability in accuracy. Thirdly, in order to assess the relationship between hits [an overdispersed count variable ($M = 21.84$, variance = 400.82)] and speed, negative binomial regression was used. The Akaike information criterion (AIC) (comparing the model for hits predicted by speed, and a model for hits including only an intercept) was used to assess whether speed explained variability in the number of hits.

3 | RESULTS AND DISCUSSION

The R95 parameter was calculated to be 58.5 m ($n = 175$, $M = 29.6$ m, $SE = 1.46$) (Figure 4).

The multivariate analysis showed hits to be a more important variable in determining accuracy than speed: terms for hits were statistically significant (Table 1), whereas speed was not statistically significant after accounting for effects of variation in hits. However, speed will influence the number of hits (Table 2): higher speeds tend to result in fewer hits, as shown in Figure 5. Figure 6 shows the observed relationship (as estimated by local polynomial regression) between static accuracy and number of hits, where lower values of accuracy imply better accuracy. Mean accuracy improves as the number of hits increases, but only up to ~25 hits. Thereafter, the mean accuracy declines for a larger number of hits.

We reason that the variance witnessed in the data is likely due to component variation and suspected temperature compensation issues with the RF components, which remain to be fully quantified in future work. That said, including a random effect to assess variability between tags, the estimated between-ID tag variance was 0, indicating no between-tag variability (i.e. no individual tag was inherently more accurate than another). Overall, the comparatively high-level accuracy

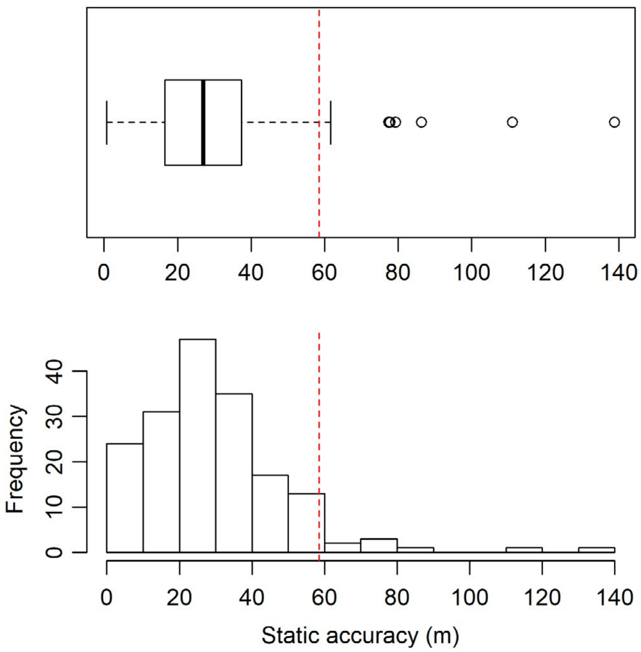

FIGURE 4 A histogram and boxplot of the static accuracy measurements, defined as the distance between each calculated tag mean coordinate produced from the RF system data and known position of the radio-frequency identification (RFID) tags. The vertical red dotted line shows the R95 parameter with a value of 58.5 m

TABLE 1 Gamma regression output. Variable hits was scaled and centred to avoid co-linearity issues. Only terms for hits were statistically significant

	Estimate	*SE*	*t* value	*p* value
(Intercept)	3.11	0.12	25.81	<0.001
Speed	0.01	0.01	0.91	0.36
Hits	-8.9×10^{-3}	3.9×10^{-3}	−2.29	0.02
Hits squared	3.7×10^{-4}	8.1×10^{-5}	4.63	<0.001

TABLE 2 Akaike information criterion (AIC) scores for the negative binomial models for the number of hits. Including variable speed vastly improves model fit, suggesting speed explains variability in the number of hits

Model	*df*	AIC
Intercept and speed	3	1,349.57
Only intercept	2	1,433.50

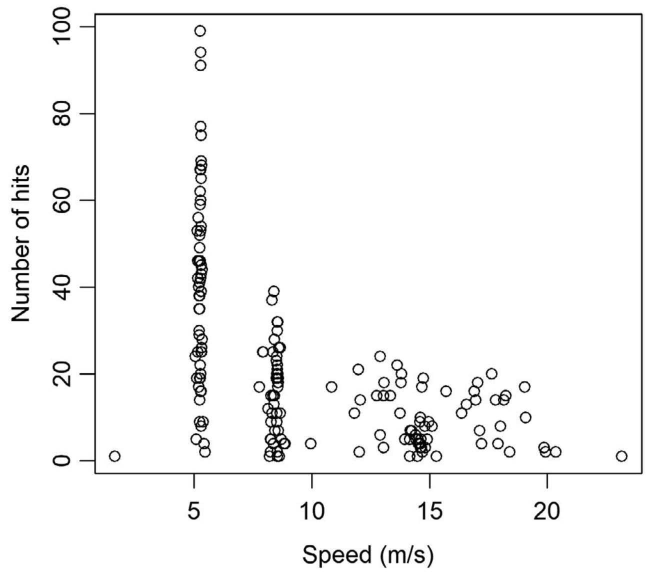

FIGURE 5 Effect of unmanned aerial vehicle (UAV) speed (m/s) on observed number of hits [i.e. each successful package received from a radio-frequency (RF) identification tag] by the RF tracking system

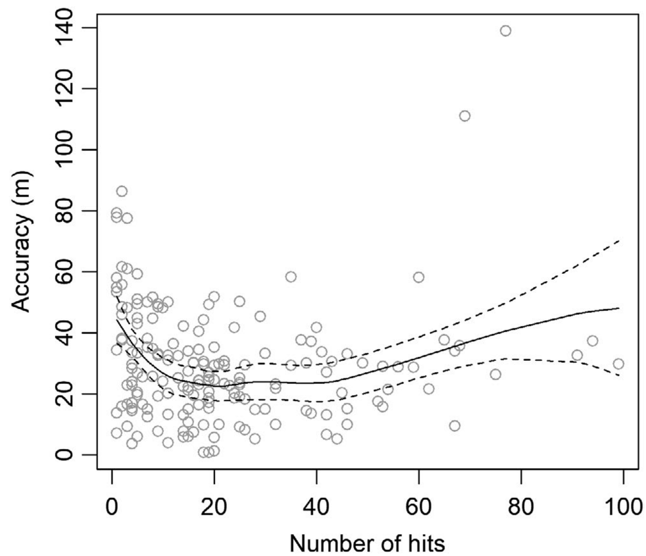

FIGURE 6 Effect of number of hits on observed static accuracy (i.e. distance between each calculated tag mean coordinate produced from the RF system data and known position of the RFID tags) of the 175 data points (m). The black line shows the observed relationship between the mean accuracy and number of hits as estimated by local polynomial regression, and the dotted lines are 95% confidence intervals

achieved as a low-cost RF-based system likely outweighs the observed variation in precision. Although further work is required, the results indicate that in considering static accuracy, increasing the number of hits (either by decreasing the time between pings transmitted on the tag trigger or decreasing UAV speed) are key factors worth exploring.

All the RFID tags attached to the management ear tags of the sheep (n = 9) and one attached to the collars were still in place at the end of the experiment (n = 2); however, none of those attached to the horns (n = 2) remained. The tags that fell off occurred before the first flight had been undertaken. Of the 10 still attached to the sheep, nine worked with 100% consistency across all seven recorded missions, whilst one failed after two missions. Tag response reliability was therefore calculated as 93%.

Since positioning is calculated from first to last response of each individual tag within the flight, only a time period and not a precise time point can be ascribed to calculated position, with the length of the time period depending on the size of the flight grid being performed. Used in conjunction with GPS systems (e.g. tracking collars), clarity could be improved. For example, GPS tracking of a small number of animals would provide a high number of consistent recordings over a time period, whereas the UAV-based RF system could deliver a lower temporal number of 'snapshot' recordings for the entire group of animals.

When preparing flight grids, specifics such as line width are comparatively minor considerations relative to the need for the grid to be large enough, and the tag trigger power to be low enough for the UAV to be able to fly out of range of the tags. A criticism of this system could be that a rough radius of all combined tags in an area must be known in order to construct a grid to cover them all. When used on ungulates (who typically herd), or in conjunction with GPS loggers already on the ground, this may be more easily definable. Furthermore, the quick reconnaissance flights could be used to identify the spread of the target group. Another limitation is that although fixed-wing UAVs are capable of a large range, the maximum grid size may be limited by the UAV operating regulations of the respective country. Although beyond visual line-of-sight (BVLOS) authorization has the potential to extend the operational capability, this is still a developing framework in many countries and therefore may not be immediately accessible. Under current circumstances flying adjacent grids of a legal size in succession is a workable alternative.

Although we have demonstrated the viability of this system across multiple UAV platforms and provided considerations for its use, several key issues would benefit from further research and development. The system's performance in situations where animals may be in shaded/covered locations (e.g. woodlands, rocky areas) needs to be investigated before it is deployed in such circumstances. In addition, integration of the RF system with the UAV autopilot modules would allow more sophisticated surveying methods, such as circling or slowing down when a tag is detected in order to increase accuracy further.

4 | CONCLUSIONS

This paper presents the first cross-platform compatible UAVRTS. Its flexibility and low-cost nature, together with the degree of accuracy achievable and proven ability to be utilized on mammals, demonstrate its readiness as a field-ready tool. Although applicable in many environments/situations, we contend that currently the suitable applications of this system would be (a) the tracking of large ungulate herds or (b) target animals, which are located in enclosures, or have defined home range areas.

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AUTHORS' CONTRIBUTIONS

B.R., M.N. and N.S. conceived the ideas and designed the methodology; B.R., N.S. and F.L. collected the data; F.L., T.C. and B.R. analysed the data; B.R. and M.F. led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

DATA AVAILABILITY STATEMENT

Data are R code used for the statistical analysis and are available on the online open access repository Figshare (Roberts et al., 2020). Also included are logic diagrams of the ear tag hardware and software, and associated pseudocode. For further enquiries regarding system design, please contact ber32@aber.ac.uk or info@ystumtec.co.uk. The DOI is https://doi.org/10.6084/m9.figshare.12712124.v3

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